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Measurement of a mixed spin-spin correlation parameter for *np* elastic scattering

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The mixed spin-spin correlation parameter $C_{\sigma\sigma} \approx 0.5C_{SS} - 0.8C_{SL}$ for *np* elastic scattering was measured for incident-neutron-beam kinetic energies of 484, 634, and 788 MeV over the center-of-mass angular range 75°–180°. These $C_{\sigma\sigma}$ data are important for determining the $I=0$ nucleon-nucleon amplitudes and provide strong constraints on the phase-shift solutions. It was found that the $^1P_1$, $^3S_1$, and $^3D_1$ isospin-0 partial waves are most strongly affected.

Nucleon-nucleon (*NN*) elastic scattering is one of the most basic reactions in the intermediate energy region (up to ~1 GeV). An unambiguous determination of the five isospin-1 ($I=1$) and five $I=0$ elastic scattering amplitudes requires a minimum of nine observables[1] in both the proton-proton (*pp*) and neutron-proton (*np*) systems at each energy and scattering angle. The $I=1$ amplitudes are fairly well known up to about 1 GeV from *pp* elastic-scattering experiments.[2–5] The $I=0$ amplitudes are poorly known, particularly above 500 MeV, as a result of insufficient data.[2,4–6] There are significant numbers of *np* differential cross section and polarization measurements, but only a few data for other spin parameters. These include results from TRIUMF[7] for energies up to 495 MeV and from LAMPF[8,9] up to 790 MeV.

A comparison of the behavior of the $I=0$ and $I=1$ *NN* amplitudes is quite important. Resonancelike behavior of the $^3P_2$, $^1D_2$, and $^3F_3$ partial waves has been seen in phase-shift analyses.[2–5,10] It has been suggested that opening of the $NN \rightarrow \pi d$ and $N\Delta$ channels, which contribute only to $I=1$, are responsible for this behavior.[11] Large inelasticities fitted to the Argand diagrams for these partial waves attest to the importance of these inelastic channels. The $I=0$ channel has a much smaller total inelastic cross section at these energies. Suggestions of resonancelike behavior for some $I=0$ partial waves have also been presented,[12] but have not been confirmed by more recent analyses. Until more $I=0$ data exist, interpretation of the behavior of the amplitudes will remain controversial.

At present, there is no coherent and tractable theory of the *NN* interaction at intermediate energies. It is hoped that QCD descriptions, for example, bag models of the nucleon,[13–15] will eventually lead to such a theory. However, to date, the predictions of these models have not agreed with experiment. Other, more phenomenological, types of analyses such as dispersion relations,[16] potential models,[17] and phase-shift parametrizations have been the most successful approaches so far.

The data discussed here are part of an ongoing program of measurements which should eventually allow a model-independent amplitude (MIA) analysis, to determine the $I=0$ *NN* amplitudes. Until a number of spin observables, sufficient to do an MIA analysis, had been measured, phase-shift predictions of unmeasured spin observables generally did not fit the *pp* data very well.[18] An MIA analysis is able to determine the amplitudes without theoretical assumptions, which are needed by the phase-shift analyses. It is another independent method for determining the amplitudes and checking the phase-shift solutions.

The experiment was performed in the polarized-neutron beam line (BR channel) at LAMPF. The experimental setup, shown in Fig. 1, was only slightly modified from that described in an earlier paper.[19] The polarized neutron beam was produced, by polarization transfer, in the $^2H(p,n)$ reaction and was scattered from a polarized proton target (HERA). The recoil protons were detected and their momentum measured in a magnetic-spectrometer system.

The laboratory coordinate system is defined by the unit vectors $\hat{L}$, $\hat{S}$, and $\hat{N}$ where $\hat{L}$ is parallel to the beam momentum, $\hat{N}$ is up, and $\hat{S}=\hat{N}\times\hat{L}$. The fields of the spin-precession magnets LORRAINE and CASTOR were adjusted to provide an $\hat{S}$ beam spin orientation upstream of the polarized target. The neutron beam polarization was 40–50% and its direction was reversed once every 2 min. Knowledge of the absolute beam polarization is tied to *np* analyzing-power data; see Ref. 20.

The polarized target material consisted of a mixture of 85% ethylamine (C_2NH_7) and 15% borane ammonia (BH_3NH_3) which gave ~16% polarizable hydrogen, by weight. The effects of polarized $^{10,11}B$ and ^{14}N in the target were estimated to be negligible.[21] The HERA superconducting magnet was rotated so that the magnetic field direction was at an angle of 37.5°, in the horizontal plane, with respect to the incident neutron beam direction. Laboratory scattering angles in the range $0° \leq \theta \leq 83°$ were observed. The coil geometry of the magnet prevented a configuration which would have allowed measurement of pure C_{SS}. Instead, a liner combination of spin-spin correlation parameters, denoted by $C_{\sigma\sigma}$, was measured. The target-polarization direction was changed (parallel and antiparallel to the field) every few hours to cancel systematic effects; its absolute value was typically 75–80%.

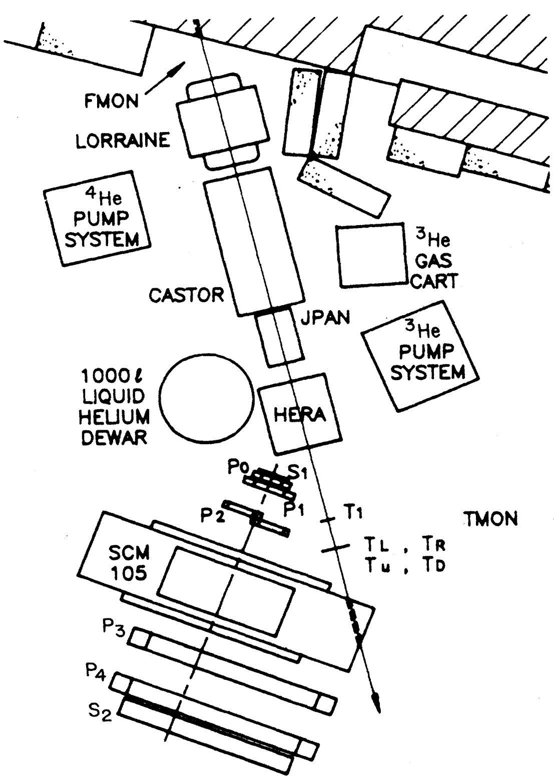

FIG. 1. Schematic diagram of the apparatus. The beam enters at the top.

Two additional chambers ($P0$ and $P3$) were added to the spectrometer system of Ref. 19. $P0$ was a multiwire proportional chamber and $P3$ was another large drift chamber, identical in construction to $P4$.[22] The presence of these additional chambers produced redundancy in the tracking of the recoil protons, which in turn gave a substantial increase in the track-reconstruction efficiency. The momentum resolution typically was found to be in the range of 1–2%.

Data were collected at 484, 634, and 788 MeV for each of the spectrometer settings, $\theta_{s,\mathrm{lab}}=10°$ and 35°. These were divided into angular bins, each subtending 5° in the center-of-mass frame. A Monte Carlo program which ray-traced elastically scattered protons through the HERA magnetic field was used to correct the scattering angles.

Missing-mass spectra were obtained for each energy, angular bin, and relative beam and target polarization. Each spectrum showed the elastically scattered neutron peak on a roughly exponential background whose shape and relative size depended on energy and angle. The typical signal-to-noise ratio at the peak was 0.7. Spectra obtained with a carbon target, for each angular bin, were used to subtract most of the background. The remaining small residual background was fitted with a quadratic polynomial by the least-squares method.

The parameter $C_{\sigma\sigma}$ was calculated using the formula

$$C_{\sigma\sigma}(\theta^*)=\frac{1}{P_bP_t}\frac{I^+(\theta^*)-I^-(\theta^*)}{I^+(\theta^*)+I^-(\theta^*)},$$

where $I^{\pm}(\theta^*)$ are the background-corrected intensities for elastic *np* scattering at a center-of-mass angle θ^*. The superscript + (−) indicates parallel (antiparallel) spin states, while P_b and P_t are the average magnitudes of the target and beam polarizations, respectively. The mixed parameter $C_{\sigma\sigma}$ can be written in the form

$$C_{\sigma\sigma}=aC_{SS}+bC_{NN}+dC_{LL}+eC_{SL},$$

where *a*, *b*, *d*, and *e* are the spin-admixture coefficients given in Table I. These coefficients were determined by calculating the precession of the neutron spin and the rotation of the scattering plane caused by the HERA magnetic field. The error bars on the data reflect the statistical uncertainty and include an estimate of the uncertainty in the background-fitting procedure. The latter uncertainty was generally small and was estimated by comparing linear and quadratic fits to the residual background. The uncertainties in the beam and target polarizations were estimated to be ~7% and ~3.3%, respectively. Combination of these in quadrature gave an overall systematic error of ±8% in the normalization of the data.

A consistency check at $\theta^*=90°$ [see Ref. 27, Eq. (19)] between various *pp* and *np* data [$C_{SS,np}$, $C_{LL,np}$, $C_{NN,pp}$, $C_{LL,pp}$, $(d\sigma/d\Omega)_{pp}$, and $(d\sigma/d\Omega)_{np}$] was satisfied to

TABLE I. Spin admixture coefficients for the C_{SS} data.

Energy (MeV)	a	b	d	e
484	0.475	0.088	0.139	−0.744
634	0.506	0.064	0.163	−0.809
788	0.528	0.050	0.178	−0.824

within 1–2 standard deviations. The *pp* elastic-scattering spin-spin correlation parameters and the differential cross sections were obtained from the SAID data base.[2]

The measured values of $C_{\sigma\sigma}$ are plotted in Fig. 2. The most recent phase-shift predictions of the VPI,[2] Basque,[23] and Saclay[24] groups and the meson-exchange model predictions of Lee and co-workers[25] and Machleidt and co-workers[26] are also shown. It should be noted that there was no 634-MeV prediction available from the Basque group. Predictions for the pure parameters C_{SS}, C_{NN}, C_{LL}, and C_{SL} at the desired scattering angles and energies were used, along with the spin admixture coefficients, to calculate $C_{\sigma\sigma}$. Tabulated values of $C_{\sigma\sigma}$ are given in Table II.

In order to determine quantitatively how well the five model predictions fit the data, the reduced χ^2 (χ^2/ν) for each prediction was calculated. None of the predictions included these data. Table III shows the χ^2/ν results. It is clear that at 484 MeV none of the predictions fit the data well, particularly for c.m. angles larger than 150°. For 634 MeV, the Saclay prediction is the best, whereas those of the VPI group and Lee and co-workers are comparable. At 788 MeV, the predictions of the VPI and Basque groups, and of Lee and co-workers, are comparable. However, at all energies, agreement with the data is only at the 2–5-standard-deviation level. It should be pointed out that there is no single group that, consistently, has the best prediction at all energies.

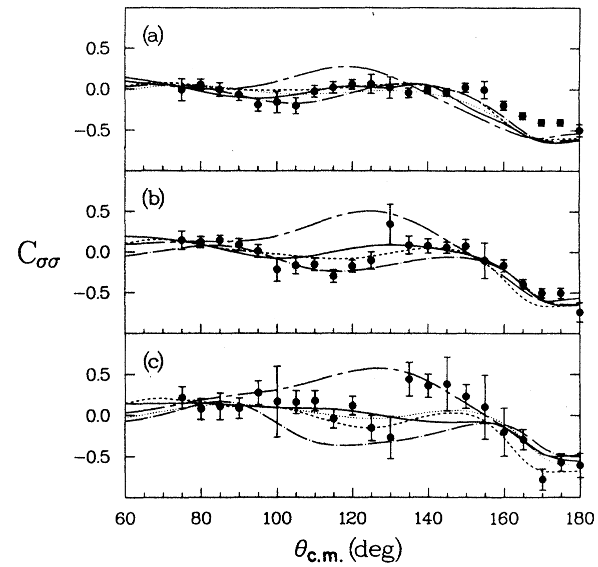

FIG. 2. Measured values of (a) 484-MeV $C_{\sigma\sigma}$, (b) 634-MeV $C_{\sigma\sigma}$, and (c) 788-MeV $C_{\sigma\sigma}$. The curves are the predictions of the VPI group (Ref. 2), solid line; the Saclay group (Ref. 24), dash-dot line; the Basque group (Ref. 23), dotted line; Lee and co-workers (Ref. 25), dashed line; and Machleidt and co-workers (Ref. 26), long-dash–short-dash line.

Values of the pure correlation parameter C_{SS} can be derived from the $C_{\sigma\sigma}$ data using experimental results[8,19] at 484 and 634 MeV. Published data for C_{LL}, C_{SL}, and

TABLE II. The $C_{\sigma\sigma}$ data at 484, 634, and 788 MeV.

$\theta_{n,\mathrm{c.m.}} \pm 0.45$ (deg)	$C_{\sigma\sigma}$ 484 MeV	$C_{\sigma\sigma}$ 634 MeV	$C_{\sigma\sigma}$ 788 MeV
180.0	−0.498 ± 0.076	−0.738 ± 0.119	−0.608 ± 0.148
175.0	−0.405 ± 0.040	−0.504 ± 0.063	−0.573 ± 0.108
170.0	−0.401 ± 0.041	−0.502 ± 0.058	−0.781 ± 0.129
165.0	−0.322 ± 0.042	−0.392 ± 0.059	−0.293 ± 0.124
160.0	−0.195 ± 0.055	−0.167 ± 0.076	−0.201 ± 0.293
155.0	−0.001 ± 0.106	−0.105 ± 0.217	. . .
150.0	0.027 ± 0.054	0.074 ± 0.084	0.231 ± 0.146
145.0	−0.030 ± 0.047	0.056 ± 0.069	0.384 ± 0.327
140.0	−0.007 ± 0.040	0.076 ± 0.088	0.362 ± 0.142
135.0	−0.038 ± 0.059	0.085 ± 0.109	0.443 ± 0.206
130.0	0.026 ± 0.131	0.341 ± 0.248	−0.268 ± 0.258
125.0	0.069 ± 0.116	−0.106 ± 0.105	−0.155 ± 0.153
120.0	0.062 ± 0.059	−0.174 ± 0.076	0.118 ± 0.114
115.0	0.025 ± 0.070	−0.297 ± 0.079	−0.042 ± 0.114
110.0	−0.021 ± 0.073	−0.152 ± 0.078	0.178 ± 0.124
105.0	. . .	−0.165 ± 0.105	0.161 ± 0.142
100.0	−0.155 ± 0.130	−0.217 ± 0.143	. . .
95.0	−0.187 ± 0.079	0.013 ± 0.078	0.276 ± 0.148
90.0	−0.064 ± 0.073	0.089 ± 0.074	0.085 ± 0.125
85.0	−0.002 ± 0.085	0.143 ± 0.061	0.109 ± 0.164
80.0	0.059 ± 0.068	0.121 ± 0.069	0.077 ± 0.128
75.0	−0.006 ± 0.135	0.146 ± 0.113	0.217 ± 0.133

TABLE III. The χ^2/ν values calculated for each model prediction to the $C_{\sigma\sigma}$ data.

Energy (MeV)	Model prediction	Degrees of freedom ν	χ^2/ν	Probability
484	VPI	21	6.79	<0.001
	Basque		6.85	<0.001
	Saclay		5.27	<0.001
	Lee and co-workers		5.52	<0.001
	Machleidt and co-workers		10.50	<0.001
634	VPI	21	2.11	~ 0.001
	Saclay		1.43	~ 0.100
	Lee and co-workers		2.29	<0.001
	Machleidt and co-workers		13.71	<0.001
788	VPI	21	1.66	~ 0.033
	Basque		1.18	~ 0.250
	Saclay		5.06	<0.001
	Lee and co-workers		1.55	~ 0.050
	Machleidt and co-workers		4.04	<0.001

C_{NN} do not exist at 788 MeV. However, the errors in C_{SS} would be dominated primarily by the uncertainties of the other component spin-spin correlation parameters.

A preliminary study of the $I=0$ phase shifts affected by these $C_{\sigma\sigma}$ data was performed with the SAID program.[2] It was found that the $^1P_1$, $^3S_1$, and $^3D_1$ partial waves were most strongly affected.

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